EFFECTS OF ADDED DAMPING SYSTEMS ON INFILLED RC FRAMES



J.-H. Park & M.-K. Kim University of Incheon, Korea

SUMMARY

The seismic response of the masonry-infilled RC frames with damping systems are investigated through extensive nonlinear time history analyses of SDOF models. The applicability of the conventional damping correction factors to those models is evaluated. The ductility demand reduction factors of the SDOF models are influenced by the intensity of the ground motions and the extent of the strength degradation as well as the natural period. The extent of the errors in the estimation of the ductility demand reduction factors using the damping correction factors is unacceptably large. Therefore, it is necessary to develop an alternative to the elastic-response-based damping correction factors to take into account the significant degradation of the stiffness and strength, which is common in masonry-infilled RC frames.

Keywords: infilled frame; damping system; nonlinear time history analysis

1. INTRODUCTION

The stiffness and strength of the masonry-infilled RC frames degrade rapidly due to the brittle behavior of the masonry materials, when the infill walls fail by the in-plane and out-of-plane action. After the masonry infill walls fail, the remaining RC frames should be able to resist the seismic load. If the capacity of the remaining RC frames is insufficient, damping systems can be utilized to reduce the seismic demand. However, degradation of the stiffness and strength needs to be taken into account in the design of the damping systems, because the effective stiffness of the inelastic system, usually represented by the secant stiffness, is closely related to the damping ratio, which plays an important role in the estimation of the reduced seismic demand.

In most design codes, reduction of the seismic demand achieved by added damping is evaluated using the ratio of the two elastic response spectra, of which one corresponds to 5 % viscous damping ratio and the other corresponds to the effective damping ratio of the integrated system to be designed. This ratio of the elastic response spectra has various terminologies, among which 'damping correction factor' is adopted in this study. Most damping correction factors are based on the linear elastic SDOF system. In case of inelastic systems, the damping correction factors are applied to the substitute systems obtained by equivalent linearization techniques. The damping correction factors proposed by Newmark and Hall (1982) are based on the ground motion amplification factors and applicable to damping ratios lower than or equal to 20%. Those damping correction factors are adopted in FEMA 273 (ATC, 1997) and ASCE/SEI 41-06 (ASCE, 2007) with minor modification and extension to higher damping ratios. Ramirez et al. (2002) proposed damping correction factors applicable up to 100% damping ratio, which are adopted in NEHRP 2000 (BSSC, 2001), ASCE 7-10 (ASCE, 2010). The damping correction factor proposed by Bommer et al. (2000) was adopted in Eurocode 8 (CEN, 2004). However, the verification of those design procedures does not include both significant degradation of the stiffness and strength and the response reduction due to the added damping systems (Ramirez et al., 2003, Lin et al., 2008, Silvestri et al., 2010, Sullivan and Lago, 2012)

In this study, the applicability of the damping correction factors obtained from elastic SDOF systems to the nonlinear SDOF systems modeling the masonry-infilled RC frames with viscous damping

systems is evaluated through extensive nonlinear time history analyses. The nonlinear SDOF system is composed of nonlinear springs corresponding to the masonry infill wall and RC frames, respectively, and a linear dashpot. Influence of various attributes of the nonlinear SDOF systems, which include the natural periods, the yield strength reduction factors, and the strength degradation ratios, on the seismic response reduction efficiency is investigated.

2. NONLINEAR SDOF SYSTEMS

The masonry-infilled RC frames with added damping systems are modeled with nonlinear SDOF systems with a unit mass. The nonlinear SDOF systems are composed of three nonlinear springs, of which one and the others represent the RC frame component and the masonry infill wall component, respectively, and a linear dashpot and an elastic spring that represent the damping systems, as illustrated in Figure 1.

2.1. SDOF Systems for the Masonry-Infilled RC Frames

The force-displacement relationship of the RC frame component is modeled with a nonlinear spring of which force-displacement relationship is represented by the Takeda 'Thin' model, which is the modified Takeda model with the most significant degradation of the stiffness and the lowest energy dissipation, considering RC frames without seismic details. The macroscopic contribution of the infill wall to force-displacement relation of the whole building is modeled with two nonlinear springs, of which hysteretic characteristics is defined by Crisafulli model (Crisafulli, 1997). Two springs are used because Crisafulli model has unsymmetrical force-displacement envelope. The tensile strength of each nonlinear spring model is assumed to be zero. The inherent damping of the nonlinear SDOF system is modeled with a tangent stiffness proportional damping coefficient in order to avoid exaggeration of the damping ratio due to the degradation of the stiffness, according to recommendation proposed by Priestley et al (2007). A sample of the force-displacement relationship of the nonlinear SDOF system is presented in Figure 2.

The force-displacement envelope for the masonry-infilled RC frame is constructed by adding those for the RC frame component and the masonry-infill wall component, as illustrated in Figure 3 (a). The combined force-displacement envelope represented by the thick solid line in Figure 3 (a) has a high initial strength provided by the masonry infill wall component and undergoes reduction of the strength after the failure of the masonry infill wall component. The curved part of the combined force-displacement envelope is idealized by multiple linear lines based on the principle of equal area, which is applied to the ascending and descending branch of the curved part, respectively, and represented in Figure 3 (b). It is assumed that the yielding of the RC frame component begins right at the complete loss of the infill wall component strength. This assumption is for the purpose of reducing the number of SDOF systems to be analyzed, and based on the report of Dolsek and Fajifar (2004) that the yield displacement does not have a significant influence to the ductility demands for the SDOF system representing the masonry-infilled RC frames.

Primary parameters for the definition of the initial SDOF systems are the natural period T_n , the yield strength reduction factor R, and the strength degradation ratio r, which are listed in Table 1. The natural period T_n is based on the initial stiffness of the multi-linear force-displacement envelope of the SDOF systems. The range of the natural periods covers those of the low- or mid-rise buildings mainly. The yield strength reduction factor R is defined by the ratio of the elastic force f_o of the corresponding linear system to the yield strength f_y of the multi-linear envelope. The strength degradation ratio r, is the ratio of the yield strength f_y for the multi-linear envelope to the yield strength f_{yf} for the RC frame component only, which is equal to the strength retained by the system after the infill loses strength completely. The ductility demand is defined for the RC frame component by

$$\mu_f = \frac{u_p}{u_{vf}} \tag{1}$$

where u_p is the peak displacement of the nonlinear SDOF systems, and u_{yf} is the yield displacement of the RC frame component. Reduction of μ_f to less than 1.0 means that the RC frames are protected to an elastic level.



Figure 1. Nonlinear SDOF system modeling masonryinfilled frames with viscous damping systems



Figure 2. Sample of the force-displacement relationships of the nonlinear SDOF systems from the time history analysis



Actual envelope (b) Multi-linearized envelope Figure 3. Envelope curve of the SDOF masonry-infilled frames

0.5

Table 1. Model parameters of the nonlinear SDOF sy	stems
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Variable	Value
Natural period T_n (sec)	0.1, 0.3, 0.5, 0.7, 1.0, 1.5, 2.0
Yield strength reduction factor R	1.5, 2, 3, 4, 5
Strength degradation ratio r	0.25, 0.50, 0.75
Normalized added damping β_d	0, 0.1, 0.2, 0.3, 0.4, 0.5

2.2. Damping Systems

The damping system is modeled with a linear dashpot and an elastic spring under the premise that diverse nonlinear dampers can be linearized as a combination of the equivalent damping and stiffness. The damping of the linear dashpot is assumed to be 0, 10, 20, 30, 40 and 50 % of the critical damping

for the RC frame component only. The critical damping for the RC frame component is based on the stiffness k_f instead of the total stiffness of both masonry infill wall and RC frame components, because the damping ratio added by the damping system may exceed 1.0 after the stiffness degrades drastically due to the failure of the masonry infill wall components. As a result, the damping coefficient of the linear dashpot c_d is expressed by the following equation.

$$c_d = 2\beta_d \sqrt{mk_f} \tag{2}$$

where β_d is the damping ratio used to defined added damping from the damping system based on the elastic stiffness of the RC frame component only.

3. GROUND MOTIONS

Simulated time histories of the ground acceleration rather than recorded ones were applied to the nonlinear time history analysis of the SDOF systems, because the former has smaller dispersion in response than the latter and is more suitable to obtain clear tendency for the seismic response of the highly nonlinear systems modeling the masonry-infilled RC frames. This basic set of the ground motion is composed of total 20 time histories that are generated to fit the design spectrum for the site class S_D of ASCE/SEI 7-10 (ASCE 2010). The spectral response at short periods S_s for the maximum considered earthquake and that at a period of 1.0 second S_1 were assumed to be 1.6 and 0.8 g, respectively. The time histories of the ground acceleration were generated using SIMQKE program with the envelope function type B proposed by Jennings (1968). Nonlinear time history analyses were conducted with RUAUMOKO program (Carr, 2007). The mean response spectrum and its deviations are plotted with the target design spectrum in Figure 4 (a), and a sample time history of the ground acceleration is plotted in Figure 4 (b).



(a) Pseudo acceleration spectra
 (b) Sample time history
 Figure 4. Simulated ground acceleration nonlinear time history analyses

4. DUCTILITY DEMANDS FOR THE NONLINEAR SDOF SYSTMES

The peak responses of the masonry-infilled RC frames with added damping systems are investigated in this section, based on the mean response obtained from the time history analyses for the basic set of the 20 simulated ground acceleration time histories. The ductility demand reduction factor is defined as a ratio between the ductility demand with and without the damping systems in order to investigate the efficiency of the damping systems, and expressed by the following equation.

$$\rho = \frac{\mu_c}{\mu_{co}} = \frac{\mu_f}{\mu_{fo}} \tag{3}$$

where μ_{co} and μ_{fo} are the ductility ratio obtained without the damping systems for the combined forcedisplacement envelope and for the RC frame component, respectively. The ductility demand reduction factors are the same for both kinds of the ductility demands. The ductility demand reduction factors are plotted in Figure 5, 6 and 7 in order to investigate influence of three parameters T_n , r and R, respectively. In figure 5, the normalized ductility demands for each combination of R and r have significant difference with respect to T_n 's, especially, between T_n 's of 0.1 sec and 0.5 sec. The difference of the normalized ductility demand among T_n 's ≥ 0.5 sec is remarkable for R = 5.0 and r =0.25, but negligible for R = 2.0 and r = 0.75. In other words, the influence of the natural period becomes more significant for lower yield strengths of the initial system compared to the ground motion intensity, and sharper drops in strength due to the collapse of the masonry infill walls. Figure 6 shows that differences among the ductility demand reduction factors is negligible with regard to three r's for a single natural period with a given level of the ultimate strength. In Figure 7, it is observed that changes in the ductility demand reduction factors with respect to R are considerable for some combinations of the natural period and the strength degradation ratio, but negligible for a relatively short period and small strength degradation as observed in Figure 7 (b). To sum up observations from Figure 5 to 7, T_n has the most significant influence to the ductility demand reduction factor, and R has an intermediate influence next to T_n , while r affects the extent of the difference among T_n 's rather than makes a difference in a single T_n .



(a) R = 2.0, r = 0.25 (b) R = 2.0, r = 0.75 (c) R = 5.0, r = 0.25 (d) R = 5.0, r = 0.75Figure 5. Ductility demand reduction factors for different T_n 's



(a) $T_n = 0.3 \text{ sec}$, R = 2.0 (b) $T_n = 0.3 \text{ sec}$, R = 5.0 (c) $T_n = 1.0 \text{ sec}$, R = 2.0 (d) $T_n = 1.0 \text{ sec}$, R = 5.0**Figure 6**. Ductility demand reduction factors for different *r*'s



(a) $T_n = 0.3 \text{ sec}$, r = 0.25 (b) $T_n = 0.3 \text{ sec}$, r = 0.75 (c) $T_n = 1.0 \text{ sec}$, r = 0.25 (d) $T_n = 1.0 \text{ sec}$, r = 0.75Figure 7. Ductility demand reduction factors for different *R*'s

5. DUCTILITY DEMANDS ESTIMATED BY THE DAMPING CORRECTION FACTORS

This section raises a question whether the damping correction factors proposed for the elastic system is applicable to the masonry-infilled RC frame structures, of which stiffness and strength degrade drastically. To answer the question, the seismic responses of the nonlinear SDOF systems with the added damping systems are estimated for the ground motions reduced by the damping correction factors, and compared with the nonlinear time history analysis results. The damping correction factor used in this study is defined by the following equation.

$$B = \frac{S_d(T, \zeta = \zeta_{eff})}{S_d(T, \zeta = 5\%)}$$
(4)

where S_d is the displacement response spectrum, T and ζ are the natural period and damping ratio of the systems, and ζ_{eff} is the effective damping ratio, which is composed of the viscous and hysteretic damping that comes from the main structural systems and the added damping systems. The damping correction factors were computed from the mean elastic response spectra for the simulated ground motions in Section 3, considering compatibility between with the nonlinear time history analysis results. The damping correction factors adopted in this study are plotted with respect to the natural periods in Figure 8 for different effective damping ratios.



Figure 8. Damping correction factors based on the elastic response spectra for simulated ground motions. ($\beta_{eff} = 0, 0.0125, 0.025, 0.05, 0.10, 0.15, \text{ and } 0.2 \text{ to } 1.0 \text{ increased by } 0.1$)

For the application of the damping correction factor, the effective damping ratio of the nonlinear SDOF system based on the secant stiffness is expressed as the sum of the inherent damping ratio and added damping ratio from the damping systems defined by Eq. (2), as follows.

$$\beta_{eff} = \beta_i + \frac{c_d}{2\sqrt{mk_{sec}}} = \beta_o \mu_c^{-0.378} + \beta_d \sqrt{\frac{k_f}{k_{sec}}}$$
(5)

where the first term is the approximate inherent damping ratio proposed by Grant et al. for Takeda 'Thin' model and decreases as the deformation grows. β_o is the elastic damping ratio equal to 0.05. On the other hand, the second term increases by the growth of the inelastic deformation, due to the decrease in the secant stiffness. The shift of the effective damping ratio due to the inelastic deformation and the added damping system changes the seismic loads. This is equivalent to the decrease of the yield strength reduction factor, and the modified yield strength reduction factor is defined by the following expression.

$$R_d = B \cdot R$$

The validity of the damping correction factors for the estimation of the seismic response of the masonry-infilled RC frames with damping systems is assessed by comparison of the actual ductility demands with the estimated ones according the following procedure.

- (1) The effective damping ratio β_{eff} of the nonlinear SDOF system with the damping system is calculated using Eq. (5) based on the mean peak displacement from the nonlinear time history analyses and corresponding force on the force-displacement envelope.
- (2) The damping correction factor *B* represented in Figure 8 is interpolated for β_{eff} .
- (3) The modified yield strength reduction factor R_d is calculated from Eq. (6).
- (4) The ductility demand on the RC frame component μ_f is interpolated for the calculated R_d based on $\mu_f R$ relationships for the nonlinear SDOF systems without damping systems.



(c) Modified yield strength reduction factors (d) Actual and estimated ductility demands **Figure 9**. Estimation of the ductility demand using the damping correction factors $(T_n = 0.5 \text{ sec}, R = 4.0, r = 0.5, k_d = 0.0)$

To illustrate the procedure of the validation, the effective damping of the SDOF system with $T_n = 0.5$ sec, R = 4.0, and r = 0.5 is plotted with respect to the damping ratio β_d in Figure 9 (a). The growth of the effective damping ratio slows down as β_d increases. The effective damping ratio is lower than 0.05 at $\beta_d = 0.0$, because the SDOF system without added damping develops large inelastic deformation and causes the ductility demand μ_c much higher than 1.0 in Eq. (5). The damping correction factor *B*'s calculated for β_{eff} 's in Figure 9 (a), and the corresponding modified yield strength reduction factor R_d 's are plotted in Figure 9 (b) and (c), respectively. The magnitude of R_d is reduced to less than 1.0 for β_d ≥ 0.2 , which means that the response of the nonlinear SDOF system is mitigated to the elastic level. The ductility demands on the RC frame component μ_f 's are plotted with respect to the yield strength reduction factor *R* in Figure 9 (d). The ordinate of the circles represents μ_f 's for the SDOF system with damping systems calculated from the nonlinear time history analyses, and the abscissa of those points corresponds to six R_d 's for $\beta_d > 0$ in Figure 9 (c) that are reduced from R = 4.0. The solid line in Figure 9 (d) plots μ_f 's versus *R*'s for the SDOF systems without the damping systems. The squares in Figure 9 (d) represent the estimated ductility demands for the SDOF systems with the damping systems that are interpolated from the solid line at the abscissas of the six circles. Considerably large differences are observed between the actual ductility demands and those estimated by the damping correction factors.



(c) $T_n = 1.0 \sec (R = 1.5, 2.0, 3.0, 4.0, 5.0)$ Figure 10. Ratios of the ductility demands versus β_d (μ_{fp} : estimation, μ_f : time history analysis)

The ductility demands on the RC frame component μ_f that are obtained from the nonlinear time history analysis of the SDOF systems with the damping systems, and their estimations denoted by μ_{fp} that are interpolated using the procedure described above are compared in Figure 10, in which the ratios of μ_{fp} to μ_f are plotted for diverse analysis conditions. In Figure 10, it is observed that the ratios of the ductility demands for the long-period systems are closer to 1.0 than those for the short period systems. The predicted ductility demands are closer to the actual one for lower *R*'s that correspond to the relatively strong system compared to the ground motions. Also, the strength degradation ratio *r* has a significant influence, as the ratios of the ductility demands for r = 0.75 are closer to 1.0 than those for r = 0.25. Consequently, the severe nonlinearity of the masonry-infilled RC frames, caused by either strong excitation or drastic strength degradation, leads to significant errors in the prediction of the seismic responses using the damping correction factors.

As far as the amount of added damping is concerned, notable characteristics are observed in many cases of Figure 10, for which the ratios of the ductility demands deviate from 1.0 at the beginning of the increase of the added damping represented by β_d , and then approach to 1.0 with further increase of β_d . In addition, it is observed that β_d corresponding to the peak deviation tends to increase for higher *R*'s. The causes of these characteristics can be presumed as follows. With lower β_d , the infill wall

components collapse earlier and have a restricted influence to the peak response. On the other hand, with much higher added damping, the response of the SDOF system is reduced to elastic deformation by the damping effect. These two extreme cases lead to weaker nonlinearity and better estimation of the ductility demands with the damping correction factor. However, intermediate added damping reduces the displacement to the region of strength degradation in the infill wall component or subsequent inelastic deformation in the RC frame component, which seems to result in relatively large errors in the estimation of the ductility demands.



(c) $T_n = 1.0 \sec (R = 1.5, 2.0, 3.0, 4.0, 5.0)$ Figure 11. Ratios of the ductility demands versus $\mu_f(\mu_{fp})$: estimation, μ_f : time history analysis)

To support these presumptions, the abscissas of the plots in Figure 10 are replaced by the ductility demands on the RC frame component and plotted in Figure 11. The broken line in Figure 11 indicate $\mu_f = 1.0$ where the infill walls are assumed to lose their strengths completely. Each line in Figure 11 approaches to $\mu_{fp}/\mu_f = 1.0$ at the maximum μ_f in the abscissa, which is obtained with the minimum β_d equal to 0.05. For R = 2.0, the maximum deviation of μ_{fp}/μ_f from 1.0 occurs at the vicinity of $\mu_f = 1.0$. However, μ_f corresponding to the maximum deviation increases to over 1.0 for higher *R*'s as observed in Figure 10. This observation implies that the infill wall has a considerable influence for certain ranges of the deformation higher than its ultimate one. Considering above observations, alternative procedures are necessary in order to replace the conventional damping correction factors for better prediction of the seismic response of the masonry-infilled RC frames with damping systems, because the errors obtained by the damping correction factors presented in Figure 10 and 11 are unacceptably

big in many cases.

6. CONCLUDING REMARKS

The applicability of the damping correction factor to the estimation of the ductility demand for the masonry-infilled frames with damping systems is evaluated through nonlinear time history analyses of the SDOF models. The ductility demands for the seismic loads reduced by the damping correction factor are interpolated from the mean ductility demands for various yield strength reduction factors. The errors of the damping correction factors in estimating ductility demands tend to increase for shorter natural periods, stronger ground motion, and more severe degradation in the strength. It was observed that the errors do not decrease only for smaller deformations close to elastic behaviour, but also for inelastic deformations much higher than the ultimate deformation of the infill wall component due to the attenuation of the infill wall's influence. Because the extent of the errors obtained from the elastic-response-based damping correction factors to take into account the significant degradation of the stiffness and strength, which is common in masonry-infilled RC frames.

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